Effect of Interconnect Linewidth on Evolution of Intragranular Microcracks Due to Electromigration Analyzed by Finite Element Method

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Abstract: The effect of interconnect linewidth on the evolution of intragranular microcracks due to surface diffusion induced by electromigration is analyzed by finite element method. The numerical results indicate that there exists critical values of the linewidth $\widehat{h}_c$, the electric field χ_c and the aspect ratio β_c. When $\widehat{h} > \widehat{h}_c, \chi < \chi_c$ or $\beta < \beta_c$, the microcrack will evolve into a stable shape as it migrates along the interconnect line. When $\widehat{h} \leqslant \widehat{h}_c, \chi \geqslant \chi_c$ or $\beta \geqslant \beta_c$, the microcrack will split into two smaller microcracks. The critical electric field, the critical aspect ratio and the splitting time have a stronger dependence on the linewidth when $\widehat{h} \leqslant 6$. In addition, the decrease of the linewidth, the increase of the electric field or the aspect ratio is beneficial to accelerate microcrack splitting, which may delay the open failure of the interconnect line.

Key words: finite element method; surface diffusion; electromigration; linewidth; microcrack evolution

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0 Introduction

The continuing development of microelectronic technology has led to a rapid reduction in the dimensions of typical integrated circuits. Interconnect lines are thin copper or aluminum alloy wires that make electrical contact between devices on a chip[1]. As the interconnect lines become thinner and narrower, the current density gets larger. Scattering by a high current density enhances atomic displacement in the direction of the electron flow. The enhanced atomic displacement and the accumulated effect of mass transport under the influence of an electric field (mainly, electric current) are called electromigration[2]. In addition, the interconnect lines inevitably exist defects, such as voids and microcracks. Electromigration might cause the defect shape change and enlarge the defects to cause open circuit failure, which is one of the most important problems for interconnect reliability.

Most of our current studies of interconnect electromigration failure mechanisms come from in situ observations of test structures using scanning electron microscopy[3-7]. Through the experiments, Zschecs et al.[3] found voids were formed at interfaces or grain boundaries and moved toward the cathode end of the line. Vanstreels et al.[4] measured migration velocity during void growth at 300 ℃. Kuwabara et al.[5] found the crack growth and gap formation occurred rapidly with increasing the average power dissipated in the wires during electromigration. The results from Yue et al.[6] showed that the electromigration-induced local degradation of microcracks in the asymmetric solder interconnects was much severer than that in the symmetrical ones. However, modeling interconnect failures posed several challenges, various models for the simulations of microstructure evolution due to electromigration have

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been developed[8-19]. Pete et al.[8] used a phenomenological model assisted by Monte Carlo-based simulations, considering the redistribution of heterogeneously nucleated voids and pre-existing vacancy clusters at the Cu cap interface during electromigration. The results indicated that this model can qualitatively explain the experimental observation as well as other reported studies. In the meanwhile, phase field model has drawn much attention. This model circumvents surface tracking by the introduction of a smooth order parameter field to describe microstructure, so it allows simulations involving evolution of arbitrary complexity. Its applications include the morphological evolution and migration of an inclusion in thin-film interconnects[9], void evolution in flip-chip solder joints under the effects of mechanical/electrical fields and surface/bulk diffusion[10], anisotropic diffusion-driven morphological evolution and migration of void defects in finite metallic film interconnects[11]. However, most of the existing models for electromigration are based on sharp interface theories, requiring an explicit tracking of microstructure surfaces during the course of the evolution. Based on this model, a three-dimensional axisymmetric finite difference numerical scheme combined with boundary element method was employed to solve the shape evolution of the pre-existing interface voids on a copper wire under electromigration[12]. Electromigration-induced void nucleation, growth and evolution have been extensively studied by finite element method[13-17] and theoretically analyzed[1-19].

Sun and Suo[20] first built a weak formulation incorporating surface diffusion and evaporation-condensation, which formed the basis of the finite element method for simulating large shape change due to surface diffusion. They developed a general finite-element program for analyzing thermal grooving on a polycrystalline surface. Their approach has since been extended and applied to a range of problems. Huang et al.[21-23] simulated the morphological evolution of two-dimensional and three-dimensional microcracks, and the results showed that microcrack evolution was not only sensitive to its initial shape but also influenced by the environment. Yu and his collaborators[24-25] found that the pore-grain boundary separation condition was insensitive to the dihedral angle and the influence of the mobility ratio of surface diffusion and evaporation-condensation on the surface grooves. He and Huang[26-27] respectively simulated the shape instabilities of intragranular microcracks due to surface diffusion induced by stress migration and electromigration, and found that the microcrack might split under certain conditions.

However, the research on electromigration in Ref.[27] was only for infinite body. With the rapid development of highly integration and miniaturization of microsystem, the interconnects become thinner, narrower and finer, so the effects of linewidth on electromigration cannot be neglected. In this paper, based on Ref.[27], the linewidth of interconnects is taken into account. Then we analyze the effect of the linewidth, the electric field and the aspect ratio on the microcrack evolution.

1 Model Description

Fig.1 shows the model of our analysis. We idealize the interconnect line as a two-dimensional single crystal with a microcrack forming symmetrically along the axis. The interconnect line is subjected to voltage V_0, and the distribution of voltage in the boundary is uniform. We assume that the electric field in the interconnect line has no component normal to the plane of the figure. Diffusion through the bulk is assumed to be negligible. For simplicity, we have assumed that the interconnect line contains no grain boundaries, the only mode of mass transport is diffusion along the microcrack surface. We have also assumed that the surface energy of the solid is isotropic and the surface energy does not interfere with the electric field energy. The interconnect line may contain one or more microcracks, whose initial shape is assumed to be known.

For simplicity, the microcrack is characterized by the aspect ratio $\beta = a/h_0$, where a is the initial semi-major axis of the microcrack and h_0 is the initial semi-minor axis. L is the length of the interconnect line, and H is the linewidth.

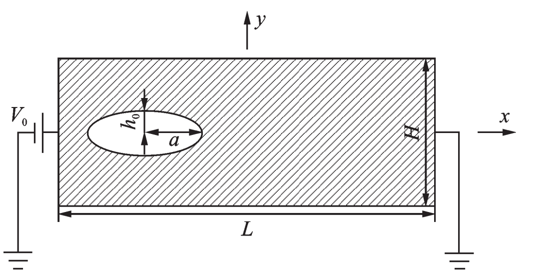

Fig.1 An intragranular microcrack in an interconnect line

2 Governing Equations and Algorithm

As shown in Fig. 2, the intragranular microcrack changes location and shape by surface diffusion on the microcrack surface. Based on Herring's classical theory[28], the kinetic law at every point on the grain surface can be described as that the flux of surface diffusion J, which is proportional to the driving force F

$$J = M \cdot F \tag{1}$$

where M is the mobility of atoms on the surface. In this paper, the mobility is assumed to be isotropic. The driving force F is defined as the free energy decrease associated with the amount of matter per unit volume moving per unit distance on the surface and is given by[20]

$$F = \frac{1}{\Omega}\gamma_s\frac{\partial k}{\partial s} - \frac{1}{\Omega^2}Z^* e\frac{\partial V}{\partial s} \tag{2}$$

where Ω is the atomic volume, γ_s is the surface energy, k is the curvature of the microcrack surface, Z^* is a phenomenological constant known as the "effective valence" of an atom, e is the charge of an electron, and V is the electrical potential.

Thus, Eq.(1) can be rewritten as

$$J = M\left(\frac{1}{\Omega}\gamma_s\frac{\partial k}{\partial s} - \frac{1}{\Omega^2}Z^* e\frac{\partial V}{\partial s}\right) \tag{3}$$

We denote the velocity normal to the microcrack surface by v_n (i. e. the volume of mass removed from unit surface area in unit time). Mass conservation requires that the surface velocity relate to the flux divergence

$$v_n = -\nabla \cdot J = M\nabla^2\left(-\gamma_s\Omega\kappa - Z^* eV\right) \tag{4}$$

The above considerations are sufficient to compute the microcrack shape history. For a given microcrack shape, the electrical potential distribution in the vicinity of the microcrack can be computed by the numerical method. Then the driving force of the atom along the microcrack surface can be determined, which drives the flux J according to the kinetic law. To conserve mass, the divergence of the flux gives rise to the surface velocity, which updates the microcrack shape for a small time increment. Repeating the procedure for many time increments, the evolving microcrack shape can be traced.

In the present investigation, the system consists of two coupled subsystems: the microcrack surface and the solid body (as shown in Fig. 2). The motion of the microcrack surface is affected by the electric potential within the solid body, which in

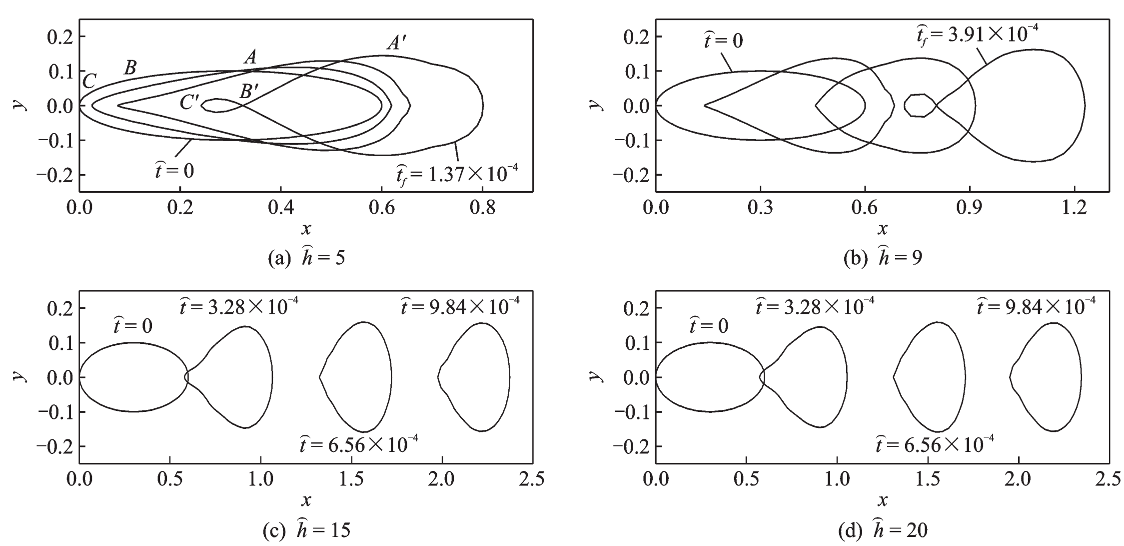

Fig.2 The evolution of intragranular microcracks with $\beta=3$ and $\chi=0.81$

turn is affected by the shape changes due to the surface motion. We use the finite element method that has been mainly implemented in our previous studies on microcrack evolutions induced by stress migration[26] and electromigration[27] in infinite solids. The specific algorithm is as follows. We choose to discretize the solid body and use the standard finite procedure. For each time step Δt, the calculations proceed. Solve the electric field on the current configuration, including the computation of the electrical potential and project the results onto the surface nodes. Then compute the new surface configuration and update the time.

3 Numerical Simulation and Discussion

Mass conservation requires that the total area of the intragranular microcrack remains constant. Therefore, the actual change of this area during simulation can be taken as a measure of the computing accuracy. We monitor the total area of the intragranular microcrack as a means to verify the accuracy of our numerical results. Large numbers of numerical calculations indicate that the finite element method used is robust, accurate and efficient. For convenience, we introduce $\hat{h}=H : h_0$ to denote the influence of the interconnect linewidth on the microcrack evolution. The relative magnitude of the two forces, the electromigration driving force and the surface tension, is given by $\chi=V_0|e|Z^*h_0/(\Omega\gamma_s L)$. Meanwhile, we introduce the non-dimensional time $\hat{t}=tM\gamma_s/h_0^4$.

3.1 Effect of linewidth

Fig. 2 shows the evolution of intragranular microcracks with $\beta=3$, $\chi=0.81$ for different values of $\hat{h}$($\hat{h}=5$, 9, 15, and 20). As shown in Fig.2(a), the initial shape of the intragranular microcrack is elliptic, so the curvature of each point on the surface is different, that is, the chemical potential is different at each point. The pronounced difference in curvature along the microcrack perimeter induces mass redistribution, with mass being removed from relatively flat microcrack surfaces and depositing in the microcrack tips. As a result, the microcrack tips recede and become blunt. In addition, the electromigration driving force is proportional to the gradient of the electric potential $\partial V/\partial s$ (See Eq.(2)). That is, $(\partial V/\partial s)_A > (\partial V/\partial s)_B > (\partial V/\partial s)_C$ in the initial time. The atoms in point A would move to point B, and then from point B to point C under the electromigration driving force. If the driving force of the electromigration is greater compared with that of the surface energy, the atomic flux from A to B is larger than that from B to C, atoms deposited on point B to form a bulge. The electric field makes atoms unceasingly gather on the bulge, in the meanwhile, the microcrack migrates along the interconnect line under the electromigration driving force. When the bulges on the upper and lower surfaces are connected at B', the microcrack cavity might split into two small intragranular microcracks as shown in Figs. 2 (a), (b). If the surface energy prevails, the intragranular microcrack tends to remain in an energy-minimizing shape as it migrates along the interconnect line as shown in Figs.2(c), (d).

Following the above analysis, there must exist a critical linewidth $\hat{h}_c$. When $\hat{h}\leqslant\hat{h}_c$, the intragranular microcrack splits into two, and the splitting time reduces as the linewidth decreases. In other words, small linewidth accelerates the splitting. In contrast, when $\hat{h}>\hat{h}_c$, the intragranular microcrack evolves into a stable shape as it migrates along the interconnect line, however, the continuing increase of the linewidth has little effect on the driving force, so the migration velocity of microcrack has no significant change with the increasing linewidth and remains a constant. Fig.3 shows the critical linewidth $\hat{h}_c$ of microcrack splitting as a function of χ for four cases of β. It indicates that $\hat{h}_c$ increases with an increase of the electric field. For a given aspect ratio, microcrack splitting will be more likely to occur with increasing the electric field. Moreover, the critical linewidth $\hat{h}_c$ increases with an increase of the aspect ratio β, that is, the increase of the aspect ratio promotes microcrack splitting.

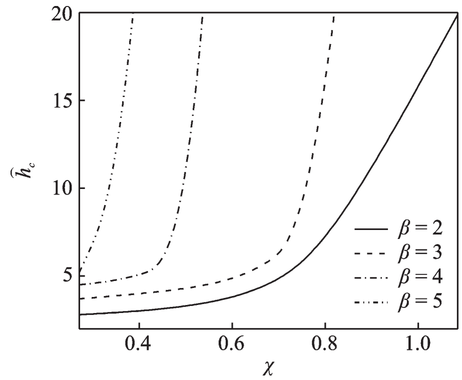

Fig.3 $\hat{h}_c$ as a function of χ

Figs.2(a) and (b) show that the splitting time of the intragranular microcrack will increase with an increase of the linewidth. Fig.4 shows the splitting time $\hat{t}_f$ as a function of the linewidth $\hat{h}$. It is obvious that the splitting time increases as the linewidth increases. This behavior indicates that the increase of the linewidth impedes the microcrack splitting process. In addition, the curves also show that the splitting time decreases as the electric field increases and the electric field accelerates microcrack splitting.

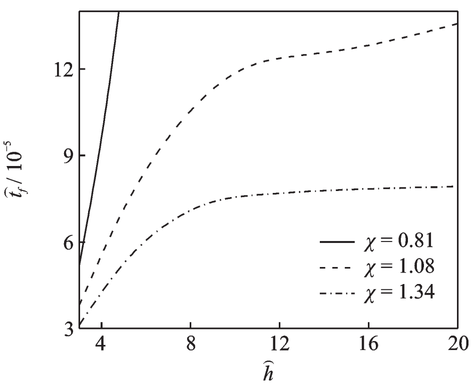

Fig.4 The splitting time $\hat{t}_f$ as a function of $\hat{h}$

3.2 Effect of electric field

Fig.5 shows the evolution of intragranular microcracks with $\beta=2$ and $\hat{h}=5$ for different values of χ=0.27, 0.54, 0.81, and 1.36. As shown in Figs.5(a) and (b), when the electric field is within a certain range, the intragranular microcrack will evolve into a stable shape as it migrates along the interconnect line. The evolution principle is the same as that of Figs.2(c) and (d). And with the increase of the electric field, the increasing driving force accelerates material motion and the intragranular microcrack migrates and changes shape more quickly.

When the electric field exceeds a certain value, microcrack splitting occurs. The splitting time decreases as the electric field increases (Figs.5(c), (d)). That is, the intragranular microcrack under a large electric field will split faster than the one under a small electric field. Through a large number of numerical simulations, we find that there exists a critical electric field χ_c for microcrack splitting. When $\chi \geqslant \chi_c$, the intragranular microcrack splits into two. In contrast, when $\chi < \chi_c$, microcrack splitting does not occur.

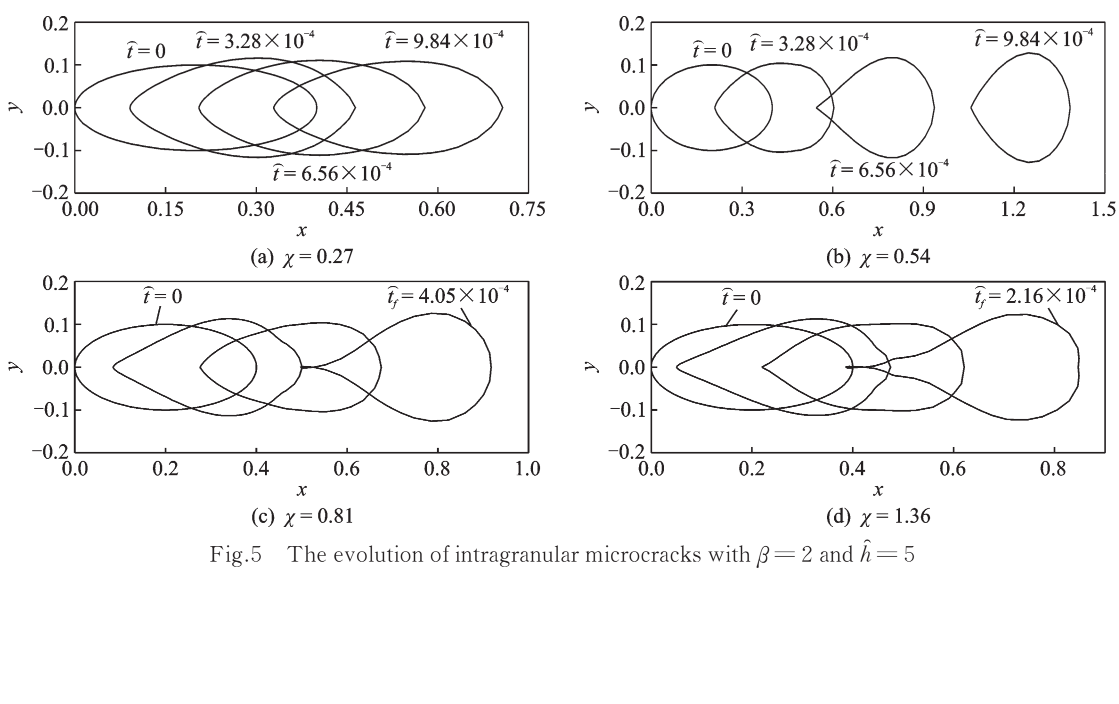

Fig.5 The evolution of intragranular microcracks with $\beta=2$ and $\hat{h}=5$

Fig. 6 shows the critical electric field χ_c of microcrack splitting as a function of $\hat{h}$ under different aspect ratios. It indicates that the critical electric field of microcrack splitting increases with increasing linewidth. For a given aspect ratio, microcrack splitting will be less likely to occur when the linewidth increases. In addition, the curves also show that the critical electric field has a stronger dependence on the linewidth when $\hat{h} \leqslant 6$. Moreover, the critical electric field χ_c decreases with an increase of the aspect ratio β and the increase of the aspect ratio is beneficial to microcrack splitting.

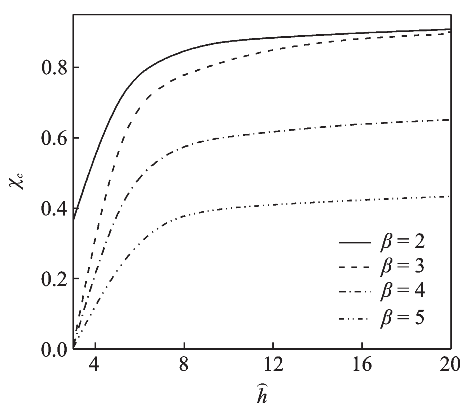

Fig.6 χ_c as a function of $\hat{h}$

3.3 Effect of aspect ratio

Fig. 7 shows the evolution of intragranular microcracks with $\chi=0.54$ and $\hat{h}=5$ for different values of β ($\beta=2$, 3, 4, and 5). The intragranular microcrack will evolve into a stable shape as it migrates along the interconnect line when the aspect ratio is within a certain range as shown in Figs. 7(a), (b). Because the chemical potential difference of the microcrack surface in the initial time increases with the aspect ratio, the driving force that induces material to migrate along the surface also increases. Therefore, the larger the aspect ratio is, the faster the microcrack migrates.

When the aspect ratio exceeds a certain range, microcrack splitting occurs. The splitting time decreases as the aspect ratio increases (Figs. 7(c), (d)). It shows that the intragranular microcrack with a large aspect ratio will split faster than the one with a small aspect ratio. Simulation results demonstrate that there exists a critical aspect ratio β_c for microcrack splitting and the intragranular microcrack splits into two when $\beta \geqslant \beta_c$. Otherwise, microcrack splitting does not occur.

Fig.8 shows the critical aspect ratio β_c of microcrack splitting as a function of $\hat{h}$ under different electric fields. It indicates that the critical aspect ratio of microcrack splitting increases with an increase of the linewidth. For a given electric field, microcrack splitting will be more difficult to occur when the linewidth increases. But the linewidth has little effect on the critical aspect ratio when $\hat{h} > 6$. Moreover, the critical aspect ratio β_c decreases with an increase of the electric field χ. That is, microcrack splitting will be more likely to occur with increasing the electric field.

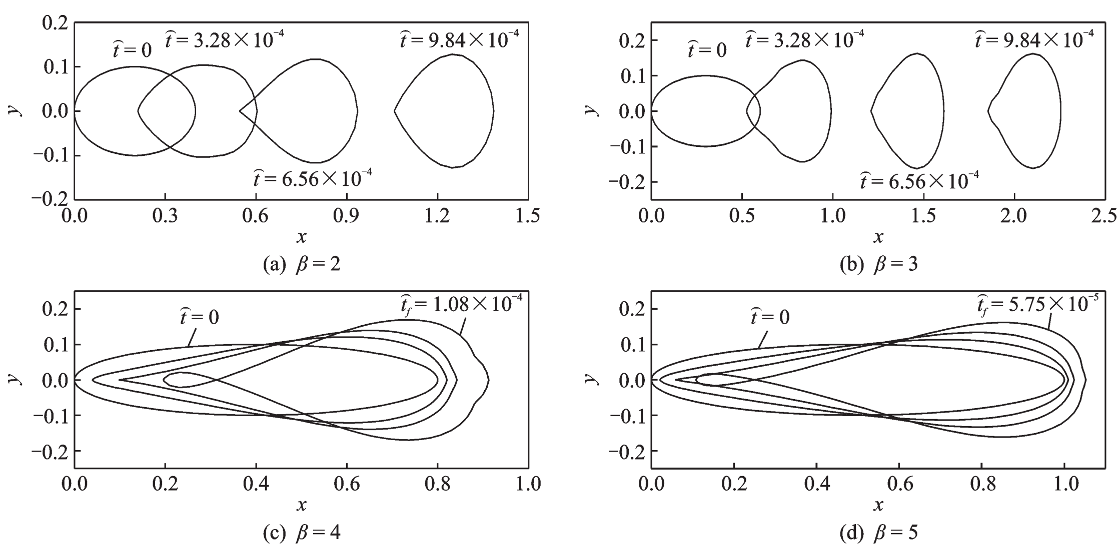

Fig.7 The evolution of intragranular microcracks with $\chi=0.54$ and $\hat{h}=5$

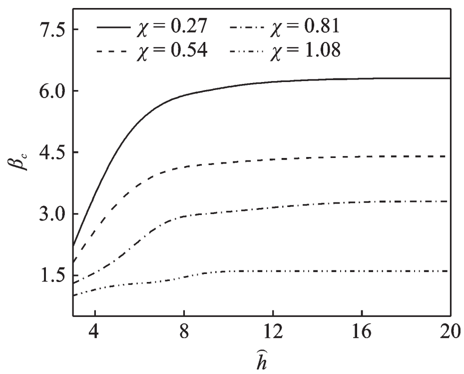

Fig.8 β_c as a function of $\hat{h}$

4 Conclusions

A two-dimensional finite element method is applied to the study of surface diffusion-controlled shape instabilities of intragranular microcracks induced by electromigration in a metal interconnect line. Unlike previously works, this paper is focused on how the interconnect linewidth influences the microcrack evolution. The main results obtained are summarized as follows:

(1) For a given electric field χ and aspect ratio β, a critical linewidth $\hat{h}_c$ exists. When $\hat{h} \leqslant \hat{h}_c$, the intragranular microcrack splits into two small parts; however, when $\hat{h} > \hat{h}_c$, the microcrack just evolves into a stable shape as it migrates along the interconnect line and the migration velocity of microcrack has no significant change with the increasing linewidth.

(2) For a given aspect ratio β and linewidth $\hat{h}$, there exists a critical electric field χ_c. When $\chi < \chi_c$, the intragranular microcrack does not split, just migrates along the interconnect line; however, when $\chi \geqslant \chi_c$, the microcrack can split into two small cavities and the electric field accelerates microcrack splitting. In addition, the critical electric field has a stronger dependence on the linewidth when $\hat{h} \leqslant 6$.

(3) For a given electric field χ and linewidth $\hat{h}$, there exists a critical aspect ratio β_c. When $\beta < \beta_c$, the intragranular microcrack just migrates along the interconnect line; however, the splitting can occur when $\beta \geqslant \beta_c$. The critical aspect ratio increases with an increase of the linewidth and the linewidth has little effect on the critical aspect ratio when $\hat{h} > 6$. The increase of the aspect ratio is beneficial to microcrack splitting.

References

[1] BHATE D N, BOWER A F, KUMAR A. A phase field model for failure in interconnect lines due to coupled diffusion mechanisms[J]. Journal of the Mechanics and Physics of Solids, 2002, 50: 2057-2083.

[2] TU K N. Recent advances on electromigration in very-large-scale-integration of interconnects[J]. Journal of Applied Physics, 2003, 94: 5451-5473.

[3] ZSCHECS E, HUBNER R, AUBEL O, et al. EM and SM induced degradation dynamics in copper interconnects studied using electron microscopy and X-Ray microscopy[C]//2010 IEEE International Reliability Physics Symposium. Anaheim, CA, USA : IEEE, 2010: 574-580.

[4] VANSTREELS K, CZARNECKI P, KIRIMURA T, et al. In-situ scanning electron microscope observation of electromigration-induced void growth in 30 nm 1/2 pitch Cu interconnect structures[J]. Journal of Applied Physics, 2014, 115(7): 213-382.

[5] KUWABARA Y, NISHIMURA S, ZAHARUDD R, et al. Investigation of electromigration in micrometer-scale metal wires by in-situ optical microscopy [C]//2011 6th IEEE International Conference on Nano/Micro Engineered and Molecular Systems. Kaohsiung, Taiwan, China: IEEE, 2011: 681-684.

[6] YUE W, QIN H, ZHOU M, et al. Electromigration induced microstructure evolution and damage in asymmetric Cu/Sn-58Bi/Cu solder interconnect under current stressing[J]. Transactions of Nonferrous Metals Society of China, 2014, 24(5): 1619-1628.

[7] ZHU X, KOTADIA H, XU S, et al. Electromigration in Sn-Ag solder thin films under high current density [J]. Thin Solid Films, 2014, 565(9): 193-201.

[8] PETE D J, HELONDE J B, VAIRAGAR A V, et al. A model for understanding electromigration-induced void evolution in dual-inlaid Cu interconnect structures[J]. Journal of Electronic Materials, 2012, 41(3): 568-572.

[9] LI Y, WANG X, LI Z. The morphological evolution and migration of inclusions in thin-film interconnects under electric loading[J]. Composites Part B, 2012, 43(3): 1213-1217.

[10] SADASIVA S, SUBBARAYAN G, JIANG L, et al. Numerical simulations of electromigration and stressmigration driven void evolution in solder interconnects[J]. Journal of Electronic Packaging, 2012, 134(2): 585-590.

[11] YANG W D, WANG X, LU G. The evolution of void defects in metallic films based on a nonlocal phase field model[J]. Engineering Fracture Mechan-

ics, 2014, 127: 12-20.

[12] CHOY J H, KAVANAGH K L, KIM Y C. Evolution of interface voids under current and temperature stress in integrated circuit metallization[J]. Metals & Materials International, 2004, 10(5): 411-415.

[13] SINGH N, BOWER A F, SHANKAR S. A three-dimensional model of electromigration and stress induced voids nucleation in interconnect structures[J]. Modelling & Simulation in Materials Science & Engineering, 2010, 18(6): 065006.

[14] WEI F L, GAN C L, TAN T L, et al. Electromigration-induced extrusion failures in Cu/low-k interconnects[J]. Journal of Applied Physics, 2008, 104(2): 023529.

[15] YAO Y, KEER L M, FINE M E. Electromigration effect on pancake type void propagation near the interface of bulk solder and intermetallic compound[J]. Journal of Applied Physics, 2009, 105(6): 063710-1-063710-8.

[16] DWYER V M. An investigation of electromigration induced void nucleation time statistics in short copper interconnects[J]. Journal of Applied Physics, 2010, 107(10): 103718-1-103718-14.

[17] MAROUDAS D. Surface morphological response of crystalline solids to mechanical stresses and electric fields[J]. Surface Science Reports, 2011, 66(8/9): 299-346.

[18] WANG Y, YAO Y. A Theoretical analysis of the electromigration-induced void morphological evolution under high current density[J]. Acta Mechanical Sinica, 2017(5): 1-11.

[19] YAO Y, WANG Y X, KEER L M, et al. An analytical method to predict electromigration-induced finger-shaped void growth in SnAgCu solder interconnect[J]. Scripta Materialia, 2015, 95(1): 7-10.

[20] SUN B, SUO Z. A finite element method for simulating interface motion-II. Large shape change due to surface diffusion[J]. Acta Materialia, 1997, 45(12): 4953-4962.

[21] DU Jiefeng, HUANG Peizhen. Effect of line width on intergranular microcrack evolution in interconnects[J]. Journal of Nanjing University of Aeronautics & Astronautics, 2017, 49(4): 518-523. (in Chinese)

[22] HUANG P Z, LI Z H, SUN J, et al. Morphological healing evolution of intragranular penny-shaped microcracks by surface diffusion: Part I. Simulation[J]. Metallurgical & Materials Transactions A, 2003, 34(2): 277-285.

[23] HUANG P Z, SUN J. A numerical analysis of intergranular penny-shaped microcrack shrinkage controlled by coupled surface and interface diffusion[J]. Metallurgical & Materials Transactions A, 2004, 35(4): 1301-1309.

[24] YU H H, SUO Z. An axisymmetric model of pore-grain boundary separation[J]. Journal of the Mechanics & Physics of Solids, 1999, 47(5): 1131-1155.

[25] LIU Z, YU H H. A numerical study on the effect of mobilities and initial profile in thin film morphology evolution[J]. Thin Solids Films, 2006, 513(1): 391-398.

[26] HE D N, HUANG P Z. A finite-element analysis of intragranular microcracks in metal interconnects due to surface diffusion induced by stress migration[J]. Computation Materials Science, 2014, 87(87): 65-71.

[27] HE D N, HUANG P Z. A finite-element analysis of in-grain microcracks caused by surface diffusion induced by electromigration[J]. International Journal of Solids & Structures, 2015, 62: 248-255.

[28] HERRING C. Surface tension as a motivation for sintering[J]. Springer Berlin Heidelberg, 1999, 27: 33-69.

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Author contributions Ms. **HE Dingni** contributed to the discussion and analysis as well as prepared all drafts. Prof. **HUANG Peizhen** contributed to the discussion and background of the study.

Competing interests The authors declare no competing interests.

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